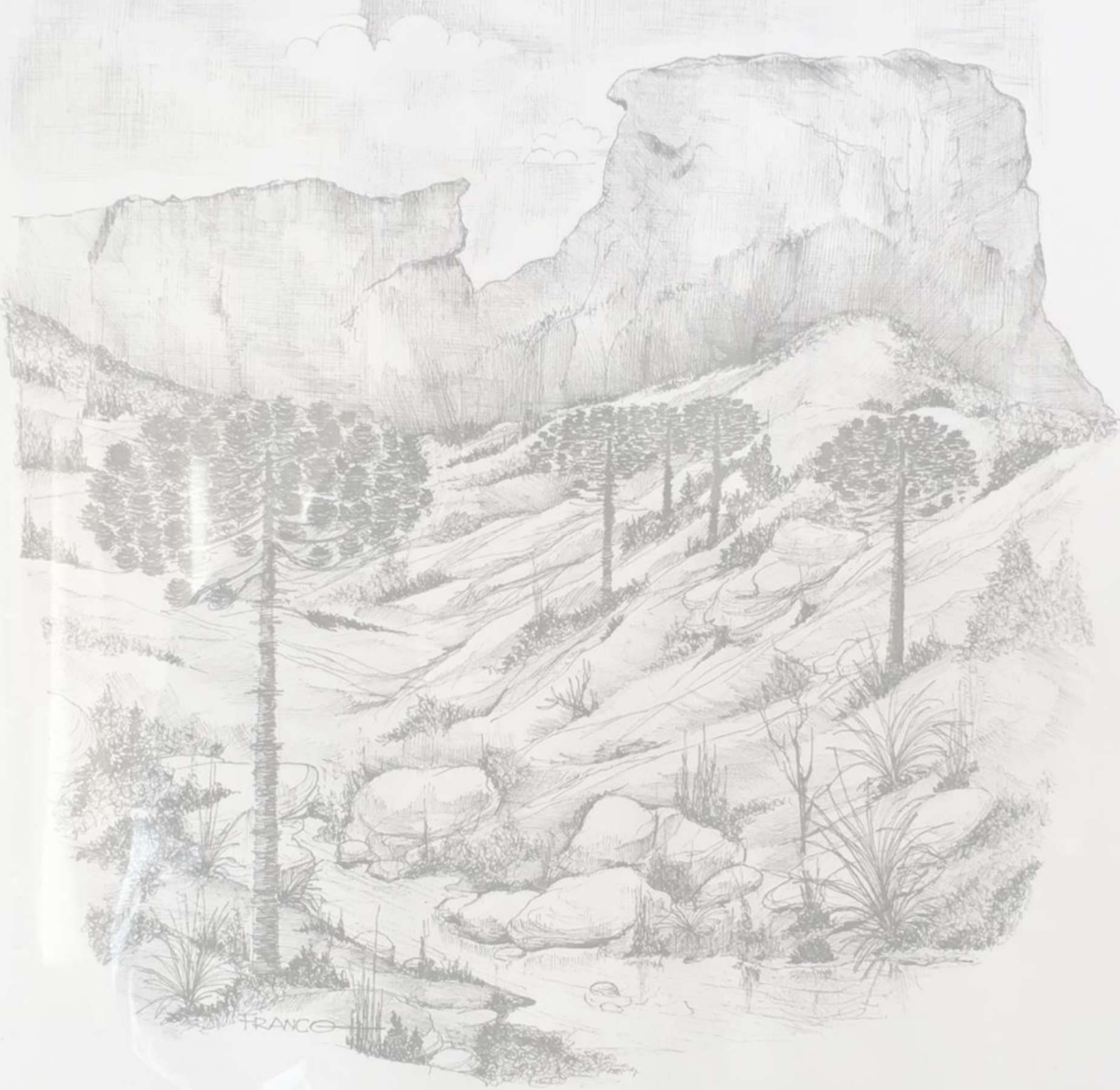
Managing the landscape across the Atlantic Forest to guarantee pollination service and biodiversity conservation



Adrian David González Chaves

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UNIVERSIDADE DE SÃO PAULO

TESE DE DOUTORADO

Managing the landscape across the Atlantic Forest to guarantee pollination service and biodiversity conservation

Manejo da paisagem ao longo da Mata Atlântica para garantir o serviço de polinização e a conservação da biodiversidade

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Autor: Adrian David GONZÁLEZ CHAVES

Orientador: Jean Paul METZGER

Coorientadora: Luísa Mafalda G. CARVALHEIRO

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Tese (Doutorado) – Instituto de Biociências da Universidade de São Paulo. Departamento de Ecologia

1. Estrutura da Paisagem
2. Mata Atlântica
3. Produção Agrícola
4. Intensificação ecológica
5. Polinização

Comissão Julgadora

Prof(a). Dr(a).

Prof(a). Dr(a).

Prof(a). Dr(a).

Prof(a). Dr(a).

Prof. Dr. Jean Paul Metzger
Orientador

Dedication

This thesis is dedicated to my parents, who once more taught me with their example than is never too late to start again, that the knowledge and experience acquired are some of the best tools to deal with uncertainties. I would also like to dedicate this work all living beings that have or will migrate at some point in their lives. May the wind provide the favorable conditions for a new beginning, and that patience makes the best while things get better.

Epigraph

"In the first years of your live, you live beneath the shadow of your past, too young to know what to do. In the last years, you find you are too old to understand the world coming at you from behind. In between there is a small and narrow beam of light that illuminates your life, that's all you have. That little beam of light in which to create the full wonder of the unique human being and the challenge in life.

The ultimate creative challenge ...

...the ultimate creative challenge is to be the architect of your own life".

shaman in Ecuador, from the book One River of Wade Davis.

Acknowledgements

I would like to first thank all the institutions that made this possible. This work was developed in the Ecology department in the Biosciences Institute of the University of São Paulo. The work was financed by the "Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Código de Financiamento 001", and FAPESP projects 2013/23457-6 & 2017/19411-1; 2018/06330-6, crucial financial support that allowed for the fully time dedication to develop this work, destined to do research on key environmental and agronomic topics for Brazilian science with the intention to benefit Brazilian society hope to have benefits beyond its borders. The work greatly benefitted from an inspiring and creative environment, the one created and maintained by the professor and colleagues from the Ecology department and the Landscape and Conservation Ecology Lab (LEPaC). In the department several student initiatives occur were crucial, for experience exchange and more importantly is a welcoming environment in which I felt at home. Moreover, the staff and the commitment of the professors and students to create an amenable space for everybody, this was particularly evident during the pandemic which extended the PhD deadlines given the increasing uncertainties that arise.

I would like to give a special thanks to the student representative at that moment: Bruna and Julia who multiply to give attend newly demand from and unprecedented global quarantine. They articulate psychological support that led to conforming mindfulness support session and afterwards with the support from the ICB somatic experience group, that allow to stablish bond that still exist until these days. I most express a double thanks to Julia for her friendship, and partnership for the long hours on discussion shared in the lab and many more adventures and great moments in international events. The lab is also filled with great personalities most of which I'm profoundly thankful to have met. Since I arrived in the LEPaC I was received with open arm, my ideas found a space to be expressed and were nurture and further expanded by the shared wish to find favorable conditions for us and the biodiversity we come from. A special shout out to current and former lab partners, Isabela, Larissa, Chico, Naty, Karine, Felipe, Catalina, Fernando, Melina, who soon became more than colleagues and were a family in which more than academics issues could be share. Also, to Marian Eiko, Douglas, Arthur, Sebastian, Clarice, Mila, Nataly, Paula, Victor, Mafe, Carito, Leandro and Mariana, always present to share laughter during the long lab hours and celebrate the small victories which were crucial to continue to the bigger goals partly express in this work.

The University is a beautiful place, not only for being a forest, highly diverse island within the largest south American city but also because the people that there arrive. In the Ecology department I had the luck to meet many great colleagues, must of which belonged to the LAGE collaboration space, where several great professor work, who also have a great institutional commitment that is both inspiring and empowering. I must send a huge hug to Andres with whom I have shared great moments and trips, but most importantly with whom the most intense part of the pandemic was lived. A special thanks to Soly, Renato, Gsus, Renan, Diana, Leticia, Pamela, Bruno, Luanne, Rodolfo, and the collegues from Bee Lab Liedson, Sheina, Rodolfo, Guaraci, Andre. I'm sure I'm forgetting many people who taught, encourage, and inspired me along this time. All crucial to keep going in the toughest moments, the same can be said for the institutional staff, Vera, Welintong, Shirlene, Erika, always there available to help with ease the struggles associated to the burocratic steps that never stop appearing.

I most thank the Argentinian family as well for making all more pleasant during my exchange period in the National University of Rio Negro at Bariloche. During the time in the Patagonian cold, I found much warmth in the house of Maxi and Jaqueline's family, with their wonderful three kids, Ana, Eliseo, and Juan. The mate, wines and long talk gave sense to live when the weather was too cloudy. Apart from their friendship, they were great landowner and neighbors while living in La Retaguardia, a shelter like house where every second lived felt like a dream came true. Special shout to the lab members of IRNAD, Matias, Pablo, Margarita, Fernanda, Facundo, and the Brazilian friends Dudu, Rafaela and Tati. I cannot leave out other biologists I met there, Cesar, Jimena and Juan.

This work greatly benefitted from the input and time of Cris Giannini, and Blande Viana from the companion committee. More importantly I was lucky to have three supervisors during the PhD. One of which is Lucas Garibaldi who acted as a supervisor during my time in Bariloche, who was also a friend who always treated me like equals, who welcomed me to his house and with whom great time was shared while driving too Yoga Classes. I have a keen interest in number and Lucas was a statistical sensei who prompted my confidence in the knowledge that have acquire, pushing me to be more confident on my work and to appropriate on was being develop. I'm deeply grateful for having the opportunity to go back to the Andes and get loosed in the valleys of the south American backbone, to have met that many great people in such intimate way. This experience greatly contributed to my maturity as a researcher, and it would have not been possible or as amazing as it was if it hadn't been for the institutional aid to undertake this academic endeavor. I was also very lucky that Luísa Carvalheiro accepted to be part of this project, she has an ease to share knowledge, provoke curiosity and improve the way to do science that always amazed me. The kindness with which she always did this was great, I would always look forward to seeing her comments and reviews as it always represented a new learning frontier.

Finally, the PhD was supervised by Jean Paul, a true character, I'm forever in debt with him. Jean was the type of supervisor that creates a great working environment and attracts wonderful people to work alongside him. One of the things I1m most grateful is the trust he gives, which give you the freedom to go after what passionate you, such freedom it can be frightening but the environment in which occurs and the strategic

guidance he provides help to keep believing in the greater good which makes maintains the engine going.
When things are on track one must be thankful, as thing don't last forever and during difficulties, we forget to appreciate what brought to us to this point. For great things to happen, some basic needs should be covered. The confidence to take on the challenge of making a PhD was not possible without the love of the family, their support was constant and always present despite the mile that separate us. I thanks to my brother her wonderful wife Danielle and my niece Clara Mei, always there with kind words and ready to make fun of me so that I don't take thing to seriously. My grandmother an inspiring woman, with whom I can share my love for the academic world and who always has a saying to continue my search. To my parents to whom the work is dedicated and their joyful spirit to take on live challenges. A deeply hearted thanks to Maria Paula who always has a smile, always there to give love and support on every aspect that my excited mine is willing to explore. Her partnership always felt present and help me to work within healthy hours to enjoy our time together. An extended thanks to Maria's family who more than one was there to create a warm environment for me to work on my thesis.

Thank you all, and by all I also include the living and non-living parts of the world we belong to and which we work to make a better place. I thank the bees that by doing their thing reminded me the vast number of coincidences that take place every second allowing us all to be here, and experience live.

Index

General Introduction

Biodiversity conservation is one of the most challenging tasks we face as humans. Probably the difficulty relays in the current western ways of life we lead, marked by the dominance of some individuals over others. What seems to be particular about us humans are the endless curiosity that has led us to pursue a lifestyle that controls the surroundings to generate the best conditions for ourselves and our society. Nonetheless, now more than ever is evident that to maintain our success as species, we need to secure the web of life we are part of. Hence, as a society, we find ourselves at a crossroads, wondering which lifestyle changes we can make to preserve that same biodiversity we rely upon. One of the most disruptive transformations we have made to the globe has been to transform the native vegetation for agricultural production. Today 40% of the terrestrial surface is farmland, with human and livestock biomass overwhelmingly surpassing the weight of wild mammals and birds (Bar-On et al., 2018).

Back in the 60ties, the late biologist Edwards Wilson and mathematician Robert McArthur contributed to synthesizing a theory that profoundly influenced biodiversity conservation and landscape planning. They described how large islands could maintain higher biodiversity communities allowing a more intricated web of interactions (mac Arthur & Wilson, 1967). The island biogeography theory grounded the design of conservation initiatives (Diamond, 1975), which was eventually challenged and led to viewing terrestrial fragments as part of a heterogeneous landscape (Haila, 2002). In the late 80s, another biologist, Monica Turner, helped redirect the attention to the interaction between ecological processes and observed patterns, more specifically towards understanding how the landscape patterns influence the biological process, which is the focus of the landscape ecology discipline (Turner, 1989). This discipline is at the core of the present work as we aim to understand how landscape management can enhance processes related to human well-being and the conservation of the web of life that we are part of.

Landscape ecology has helped guide conservation initiatives, biological invasion management, and ecological restoration, something so desperately needed in this time when zoonotic diseases have a global impact, despite existing regional evidence of landscape patterns influencing health issues (Crouzeilles & Curran, 2016; Didham et al., 2007; Ferreira et al., 2021; Prist et al., 2021; Ribeiro et al., 2019; Ribeiro Prist et al., 2022). This work aims to provide evidence and tools on where and how landscape management can contribute to finding synergies between native vegetation conservation and agricultural production, the most relevant factor threatening biological conservation (Hoang & Kanemoto, 2021).

Technological advances allow the transmission of human-induced or natural transformation almost simultaneously across the globe, such as a volcanic eruption in the middle of the Pacific Ocean (Tonga, January 2022) or detecting the location of large areas of the Amazon being cut down (MapbiomasAlert.org). Detrimental effects of landscape transformation on biodiversity loss have long been documented (Donaldson et al., 2016). The pressing need for pathways that contribute to reverting human-induced impacts on biodiversity demands evidence of more optimist realities, like where regenerating forests have more recovering success (Díaz et al., 2019) or where biodiversity contributes to agricultural production through pollination and pest control. They all share a governance limitation of articulating local-level actions with regional goals to safeguard the biodiversity that remains (Bennett et al., 2015; Isbell et al., 2017). To help guide local efforts that best contribute to achieving regional goals, we have focused on forest conservation contribution to crop yields.

Animal pollination is a vital ecosystem service that generates revenue from agricultural production while guaranteeing the production of many nutrients related to human well-being (Dicks et al., 2021; Potts et al., 2016). Multiple insect species pollinate most pollinator-dependent crops; thus, their fruit set relies on the flower visitors' abundance and diversity (Garibaldi et al., 2013; Garibaldi et al., 2016). Managed bee species like *Apis mellifera* have been used to increase the productivity of such crops. However, this species is only a suitable pollinator for some crop species (Giannini et al., 2014; Rader et al., 2015). Moreover, for most pollinator-dependent crops (Aizen & Harder, 2009), there is a need to maintain a higher diversity of flower visitors to increase temporal and spatial stability in flower visitation rate (Dainese et al., 2019; Klein et al., 2009). Conserving animal pollinators is thus crucial to account for the increasing animal pollination demands (Aizen et al., 2019). For instance, in Brazil, pollinators are estimated to contribute economically with around 30% of the annual agricultural income (Giannini et al., 2015, 2017), but this assumes that highly simplified landscapes still provide animal pollination.

A potential pollination service crisis can reduce agricultural production in Brazil by 16-51 million tons resulting in a loss of agricultural contribution to the Brazilian Gross Domestic Product (GDP) by 6% to 19% (Novais et al., 2016). Despite that, and neglecting suggestions made by previous studies (Carvalheiro et al., 2012; Garibaldi et al., 2014; Thomas & Kevan, 2012), the management of both bees and pollination services has not been a major target incorporated in conservation policies nor on crop management plans (but see http://www.operationpollinator.com/ from Syngenta). Probably because of the limited communication between academics and practitioners. However, it could also be attributed to a mismatch between the scale at which we understand biodiversity contribution to crop yields and the scale at which conservation initiatives are implemented (Isbell et al., 2017). Therefore, we aimed to relate landscape metrics known to affect biodiversity and service provision at a local scale with regional agricultural productivity to provide a spatial assessment of where pollination service could be boosted by landscape management (Breeze et al., 2016; Lautenbach et al., 2012).

There is a need to manage the land towards win-win scenarios by promoting both ecosystem service provision and biodiversity conservation (Senapathi et al., 2015). Achieving higher yields by enhancing biodiversity-based ecosystem services is at the core of the Sustainable Development Goals and nature-based solutions (Bommarco et al., 2013; DeClerck et al., 2016;

Escobedo et al., 2019; Garbach et al., 2016; Keesstra et al., 2018). Landscape management is among the most critical components of achieving ecological intensification (Bommarco et al., 2013) and can help maintain a high diversity of pollinators that could subsequently enhance productivity (Garibaldi et al., 2011; Mitchell et al., 2015; Ricketts et al., 2008). For instance, landscapes with less than 20 to 30% of natural vegetation have reduced community integrity (Banks-Leite et al., 2014). What remains to be tested is whether this biodiversity loss affects regional agricultural yields.

This work aims to generate knowledge that articulates local management practices and landscape composition and configuration at a larger scale to achieve pollination service provision and biodiversity conservation (e.g., the desired win-win situation) (Ekroos et al., 2016; Geertsema et al., 2016). We also aim to improve our ability to predict changes in **ecosystem service provision** by studying cropland productivity, which can help promote the development of incentives and policies that benefit forest conservation and pollination service management. We will evaluate synergies between forest conservation and agricultural productivity in one of the most diverse and threatened biomes in the world, the Brazilian Atlantic Forest. More specifically, we propose to answer three main questions:

(i) What is the relative importance of forest conservation compared to climatic conditions and management practices in predicting coffee productivity across the Atlantic Forest?

(ii) What is the relevance of mature forest conservation, and where are the best areas where forest regeneration can contribute to coffee productivity?

(iii) How does forest conservation contribute to temporal crop yield stability?

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Conclusion

Brazil is one of the largest crop producers in the world, and tension between the agricultural lobby and conservation continues to exist (Metzger et al., 2019). This work addressed the spatial and temporal contribution of the Atlantic Forest to agricultural production along a gradient of climatic and soil characteristics at an unprecedented scale. With this work, we intended to identify where synergies between conservation and agriculture occur and provide evidence that forest conservation has underpinned the region's economic development (Sparovek et al., 2012). We demonstrated that the municipalities with the highest coffee productivity preserve more than 20% of the forest in the coffee fields' surroundings and provided evidence that pollinators are central to such synergies (Chapter 1). Moreover, we show the importance of conserving mature forests to guarantee ecosystem service provision and indicate where forest regrowth has contributed to enhancing coffee yields (Chapter 2). Finally, we showed that the Atlantic Forest helps stabilize crop yield across the years. In municipalities with lots of interspersion between crop fields and forests, landscape configuration helps with this crop yield stability (Chapter 3).

The first chapter's results emphasize landscape management's vital role in agricultural planning. We found that forest fragments were more relevant for predicting coffee yields than management practices like pesticide use, irrigation, and organic management. Moreover, the positive effect of forest conservation on yields was consistent across the climatic and soil conditions of the 610 municipalities considered. Over the past years, efforts have been made to consider pollination service as an agronomic input that needs to be managed, which was often lacking in the agricultural literature (Garibaldi et al., 2020; Ratto et al., 2022). We have shown that forest conservation underpins ecosystem services provision at an unprecedented scale by combining regional maps and governmental databases. Although extensive literature exists on the benefits of natural habitat conservation on biodiversity and ecosystem services, our methodological approach showed that forest conservation is crucial for 20% of the world's coffee production (González-Chaves et al., 2022).

The moment this work is being completed cannot be more accurate. According to the United Nations, we are in the decade of forest restoration, and pathways to implement and achieve restoration goals are needed more than ever. Considering that much of the restoration will have to occur in private lands, providing guidance, with farmers' participation, on where restoration would contribute to agricultural production and stability is crucial (Erbaugh et al., 2020). Our second chapter provides some insights into this increasing demand. Apart from reinforcing the importance of conserving mature forest fragments (Barlow et al., 2007), we suggest there is a delay in regenerating forest fragments to provide ecosystem services. However, young regenerating forest fragments can enhance the landscape's ability to provide ecosystem services, probably by facilitating the movement of pollinators through the landscape and providing additional floral resources, which would enhance pollinator populations and increase crop productivity.

Temporal dynamics are among the less studied topics in the ecosystem services literature (Boesing et al., 2020), probably by the difficulty of getting long-term data. We have tackled this limitation by integrating temporal national databases (from the Brazilian Institute of Geography and Statistics - IBGE) with recently available annual land use maps (Mapbiomas.org). Previous works have shown that the productivity of crops highly dependent on pollinators is the most unstable from year to year (Garibaldi et al., 2011). Here we showed that forests in the landscape considerably reduce this instability, making them as stable as crops that do not depend on animal pollinators. Furthermore, we showed that the spatial arrangement of forest fragments is the most relevant for contributing to crop yield temporal stability with higher forest fragmentation in landscapes with at least 20% forest cover being a convenient design for multiple benefits. Preserving higher forest patch densities (e.g., higher forest fragmentation) and designing crop fields closer to the forest to facilitate the spillover of pollinators towards crops fields can enhance spatiotemporal stability. Considering that the demand for pollinated crops is rising (Aizen et al., 2019) and the landscape is becoming more simplified, securing forests within working landscapes is crucial to guarantee food sovereignty for years.

The present work aims to subsidize public policies and market programs to enhance ecosystem services in agricultural landscapes. We could identify where the forest is already contributing to stabilizing crop productivity spatially and temporally and where restoration would be needed to secure future crop production. Our analyses also have direct implications for farmers as we provide landscape management guidance at small, local scales on how agricultural production can benefit from the presence of the forest. Moreover, as traceability becomes the central tool for sustainable food chain systems, our work provides the methodological basis to detect crop production benefits from pollination services (Gardner et al., 2019).

It is noteworthy that the interpretations and mechanisms from the correlations found are all based on field studies seeking to understand landscape-biodiversity-ecosystem services relationships at the landscape (*see* González-Chaves et al., 2020; see also interface project http://ecologia.ib.usp.br/projetointerface/). Thus, as we hope to incentivize big datasets to monitor restoration, agricultural, and conservation goals, we would like to remind the importance of field experiments to backup future regional assessments.

A few arthropod species are individually managed to provide services, like pollination and pest control, regardless of wild pollinators present in the landscape, raising concern about ecosystems service's ability to conserve biodiversity (Kleijn et al., 2015). We strongly recommend managing ecosystem service by enhancing ecosystem resilience through landscape planning for biodiversity conservation (Senapathi et al., 2015). We have used governmental databases and corroborated that the landscape structure of a biodiversity hotspot can be regionally planned to guarantee native vegetation conservation and agricultural goals.

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Abstract

Agriculture is the most dominant land use system across the globe, which continues to put pressure on native ecosystems. Understanding where biodiversity conservation contributes to agricultural production is crucial to engage farmers in conservation initiatives and to define areas which would benefit from ecosystem restoration. Field experiments across the globe suggest that maintaining natural habitats in the agricultural landscapes enhances crop yields through services like pollination and pest control. We aim to understand whether the spatial relationship is maintained across large regions and assessed the temporal variations of the importance of landscape features at influencing agricultural productivity. Using available data set on crop productivity from governmental organizations and non-governmental initiatives we gathered data on crop locations and the Atlantic Forest remains and demonstrated that the presence of tropical forest is positively associated agricultural yields across a climatic and soil characteristic gradient. We further showed that forest cover was more relevant at predicting coffee yields than agricultural management practices, like irrigation, pesticide use, organic manure among others. Moreover, the effects of forest cover are higher for municipalities producing coffee species which are highly dependent of animal pollination. On the second chapter we assessed the importance of forest fragments age at predicting coffee yields, and corroborate the importance of conserving mature forest fragments, as young regenerating fragments can only enhance coffee yields when municipalities are above the biodiversity extinction threshold. Finally, we explored the role of forest conservation on temporal stability of agricultural productivity by analyzing the 16 main crops produced in the whole Atlantic Forest. Not only did we find that the presence of forest fragments in the municipalities is crucial for crop productivity to be more stable across time, but also that a higher interspersion is most favorable for crop that fully dependent on pollinators. Probably such landscape features favor biodiversity spillover from forest fragments towards cropland and help guaranteeing yield enhancement. This work provides regional evidence of the role of landscape features for planning agricultural production and complement biodiversity conservation actions. We further reinforce the role of forest conservation for achieving ecological intensification of agriculture that are so much needed to halt the detrimental effects that agriculture have had on biodiversity. We have shown that synergies between conservation and agriculture exist and have been crucial for one of the largest crops producing regions of the world. We believe our work can help in the development of agricultural and environmental policies, to define economical goals through the enhancement of biodiversity.

Resumo

A agricultura é o uso da terra predominante, que continua a exercer pressão sobre os ecossistemas nativos. Compreender onde a conservação da biodiversidade contribui para a produtividade agrícola é crucial para promover o envolvimento de agricultores nas iniciativas de conservação e para definir áreas que poderiam se beneficiar da restauração. Experimentos de campo ao redeador do mundo sugerem que manter os habitats naturais nas paisagens agrícolas aumenta a produtividade agrícola através da provisão de serviços ecossistêmicos como polinização e controle de pragas. Pretendemos entender se a relação espacial entre biodiversidade e serviços ecossistêmicos é constante ao longo da Mata Atlântica, e avaliar as variações temporais na provisão de serviços ecossistêmicos. Usamos data governamental disponível sobre à produtividade agrícola e mapas de uso da terra, de Organizações não governamentais, da distribuição espacial dos remanescentes de Mata Atlântica para demonstrar o papel da conservação da biodiversidade na produção agrícola. Além disso, demonstramos que a cobertura florestal é fundamental para predizer a produtividade de café, por cima de práticas de manejo como irrigação, uso de pesticidas, manejo orgânico, entre outros. Os efeitos positivos da cobertura florestal foram maiores nos cultivos altamente dependentes de polinizadores. No segundo capítulo, avaliamos a importância de preservar florestas maduras, já que florestas regenerantes jovens só contribuem para a produtividade em municípios acima do limiar de extinção da biodiversidade (>20%). Finalmente no terceiro capítulo, viemos que a estabilidade anual da produtividade agrícola era maior na presença da Mata Atlântica. Os municípios com maior estabilidade temporal da agricultura têm maior densidade de Mata o que acontece principalmente em paisagens com 20% de florestas. Provavelmente a configuração interpresa de floretas e áreas de cultivos está favorecendo o descolamento dos polinizadores há os cultivos, já os cultivos altamente dependentes de polinizadores se-beneficiaram mais da presença das florestas. Esse trabalho provê evidências regionais do papel da estrutura da paisagem para planificar a produção agrícola junto com a conservação da biodiversidade. A conservação da vegetação nativa é central para alcançar a intensificação ecológica da agricultura que tanto precisamos para amenizar os impactos negativos dos sistemas agrícolas na biodiversidade. Temos demonstrado a existência de sinergias entre conservação e agricultura, numa das principais regiões agrícolas do mundo e hotspot da biodiversidade. Acreditamos que nosso trabalho pode ajudar no desenvolvimento de políticas ambientais e agrícolas, para definir metas econômicas baseadas na proteção da biodiversidade.